

# Prospect of $D^0$ mixing and $CPV$ at LHCb

Patrick Spradlin<sup>a</sup>

*Particle Physics Department, University of Oxford, Denys Wilkinson Building, Keble Road  
Oxford OX1 3RH, United Kingdom  
Patrick.Spradlin@cern.ch*

## Abstract

Precision measurements in charm physics offer a window into a unique sector of potential New Physics interactions. LHCb is poised to become a world leading experiment for charm studies, recording enormous statistics with a detector tailored for flavor physics. This article presents recent charm  $CPV$  and mixing studies from LHCb, including LHCb's first  $CP$  asymmetry measurement with  $37 \text{ pb}^{-1}$  of data collected in 2010. The difference of the  $CP$  asymmetries of  $D^0$  decays to the  $K^-K^+$  and  $\pi^-\pi^+$  final states is determined to be  $\Delta\mathcal{A}_{CP} = (-0.28 \pm 0.70 \pm 0.25)\%$ . Significant updates to the material presented at the 4<sup>th</sup> International Workshop on Charm Physics are included.

## 1 The LHCb experiment

LHCb, the dedicated flavor experiment at CERN's Large Hadron Collider (LHC), is the only LHC experiment currently performing measurements of charm  $CP$  violation ( $CPV$ ) and  $D^0$ - $\bar{D}^0$  mixing. Many of the features that make LHCb an excellent B-physics laboratory also make it well-suited for precision charm physics studies.<sup>1</sup> The cross-section to produce charm hadrons into the LHCb acceptance in the LHC's  $\sqrt{s} = 7 \text{ TeV}$  proton-proton collisions is  $1.23 \pm 0.19 \text{ mb}$ , creating a huge potential data set.<sup>2</sup> The LHCb trigger system has a flexible design that includes dedicated charm triggers so that this prolific production can be exploited.

LHCb recorded a total integrated luminosity of  $37.7 \text{ pb}^{-1}$  in 2010. These data were collected under rapidly evolving interaction conditions as the LHC provided high quality beams with increasing bunch numbers and intensities. Large charm data sets were collected in 2010, and the 2011-12 run promises to yield even larger samples of charm decays, with a target of  $1 \text{ fb}^{-1}$ .

## 2 Time-integrated $CPV$ in D mesons

LHCb is searching for evidence of new sources of  $CP$  asymmetry in the time-integrated decay rates of D mesons. For a given final state  $f$ , the time-integrated  $CP$  asymmetry,  $\mathcal{A}_{CP}(f)$ , is defined as

$$\mathcal{A}_{CP}(f) = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}. \quad (1)$$

For  $D_{(s)}^+$  mesons this is a measurement of direct  $CPV$ , while  $D^0$  decays may have contributions from both indirect and direct  $CPV$ . In the Standard Model,  $CPV$  in the charm system is highly suppressed. Indirect  $CPV$  is negligibly small and should be common for all decay modes. Direct  $CPV$  is expected to be  $\mathcal{O}(10^{-3})$  or less and to vary among decay modes.<sup>3</sup> In  $CPV$  searches in singly Cabibbo suppressed decays, such as  $D^0 \rightarrow K^-K^+$ , participation of well-motivated new physics (NP) particles in the interfering penguin amplitude could enhance direct  $CPV$  up to  $\mathcal{O}(10^{-2})$ .<sup>4</sup>

LHCb recently presented its first results of time-integrated  $CPV$  measurements in decays  $D^0 \rightarrow K^-K^+$  and  $D^0 \rightarrow \pi^-\pi^+$ .<sup>5</sup> The analysis uses  $D^0$  mesons reconstructed as the product of  $D^{*+} \rightarrow D^0\pi_{\text{slow}}^+$  decays so that their initial flavors are identified (tagged) as  $D^0$  or  $\bar{D}^0$  by the

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<sup>a</sup>On behalf of the LHCb collaboration.

charge of the tagging slow pion. The asymmetries of the  $D^*$ -tagged raw yields,  $\mathcal{A}_{\text{Raw}}^*$ , can be written as a sum of components:

$$\mathcal{A}_{\text{Raw}}^*(f) = \mathcal{A}_{CP}(f) + \mathcal{A}_D(f) + \mathcal{A}_D(\pi_{\text{slow}}) + \mathcal{A}_P(D^{*+}), \quad (2)$$

where  $\mathcal{A}_D(f)$  and  $\mathcal{A}_D(\pi_{\text{slow}})$  are the detection asymmetries of the final state  $f$  and the tagging pion  $\pi_{\text{slow}}^\pm$  respectively and  $\mathcal{A}_P(D^{*+})$  is the production asymmetry of  $D^{*+}$ . For the self-conjugate final states  $K^-K^+$  and  $\pi^-\pi^+$ ,  $\mathcal{A}_D(K^-K^+) = \mathcal{A}_D(\pi^-\pi^+) = 0$ . The production asymmetries  $\mathcal{A}_P$  are independent of final state, as is  $\mathcal{A}_D(\pi_{\text{slow}})$ . Hence, the difference in  $\mathcal{A}_{CP}(f)$  for  $f = K^-K^+$  and  $\pi^-\pi^+$  can be measured precisely with the confounding systematic asymmetries canceling exactly:

$$\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(K^-K^+) - \mathcal{A}_{CP}(\pi^-\pi^+), \quad (3)$$

$$= \mathcal{A}_{\text{Raw}}^*(K^-K^+) - \mathcal{A}_{\text{Raw}}^*(\pi^-\pi^+). \quad (4)$$

In  $37 \text{ pb}^{-1}$  of LHCb 2010 data, we measure  $\Delta\mathcal{A}_{CP}$  consistent with zero:

$$\Delta\mathcal{A}_{CP} = (-0.28 \pm 0.70 \pm 0.25) \%, \quad (5)$$

where the first uncertainty is statistical and the second is systematic. This result is approaching the sensitivity of  $CPV$  measurements performed by the B-factories in these decay modes,<sup>6,7</sup> but not yet at the level of CDF's recent measurement.<sup>8</sup> Due to differential proper-time acceptance between the  $K^-K^+$  and  $\pi^-\pi^+$  samples, the measured value of  $\Delta\mathcal{A}_{CP}$  includes a residual 10% of the mode-independent indirect  $CP$  asymmetry. No limiting systematic bias has been identified in the method, so future iterations of the measurement with the much larger data set anticipated for 2011-2012 will be significantly more precise.

### 3 Time-dependent $CPV$ and mixing measurements in $D^0$

The conventional parameterization of charm mixing is fully explained elsewhere.<sup>9</sup> Briefly, the mass eigenstates of the neutral D system  $D_1$  and  $D_2$  are expressed as normalized superpositions of the flavor eigenstates  $D^0$  and  $\bar{D}^0$ :

$$D_1 = pD^0 + q\bar{D}^0, \quad D_2 = pD^0 - q\bar{D}^0, \quad (6)$$

where  $p$  and  $q$  are complex scalars,  $|p|^2 + |q|^2 = 1$ . Letting  $m_{1,2}$  and  $\Gamma_{1,2}$  represent respectively the masses and widths of the mass eigenstates  $D_{1,2}$ , mixing is usually parameterized by the real quantities  $x$  and  $y$ :

$$x \equiv \frac{m_1 - m_2}{\Gamma}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \quad (7)$$

where  $\Gamma \equiv \frac{1}{2}(\Gamma_1 + \Gamma_2)$ .  $CP$  is violated in the mixing if  $\left|\frac{q}{p}\right| \neq 1$ .  $CPV$  in the interference between mixing and direct decay is parameterized by a real phase  $\phi$ , which is zero if  $CP$  is conserved. The relative argument of  $q$  and  $p$  is conventionally chosen equal to this phase,  $\arg \frac{q}{p} = \phi$ .

LHCb is working towards its first measurements of  $CPV$  and mixing in  $D^0$ - $\bar{D}^0$  with lifetime ratios of  $D^0 \rightarrow K^-\pi^+$  and  $D^0 \rightarrow K^-K^+$  decays. The lifetime of decays to the  $CP$ -even eigenstate  $K^-K^+$ ,  $\tau(K^-K^+)$ , is related to the lifetime of the flavor-specific final state  $K^-\pi^+$ ,  $\tau(K^-\pi^+)$ , by the mixing parameters:

$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = y \cos \phi - \frac{1}{2} \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) x \sin \phi. \quad (8)$$

If  $CP$  is conserved,  $y_{CP} = y$ . The asymmetry in the lifetimes of  $D^0$  and  $\bar{D}^0$  decays to the  $CP$  eigenstate  $K^-K^+$  is related to the  $CPV$  and mixing parameters by

$$A_\Gamma \equiv \frac{\tau(\bar{D}^0 \rightarrow K^-K^+) - \tau(D^0 \rightarrow K^-K^+)}{\tau(\bar{D}^0 \rightarrow K^-K^+) + \tau(D^0 \rightarrow K^-K^+)} = \frac{1}{2} \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) y \cos \phi - x \sin \phi. \quad (9)$$

$D^*$ -tagged candidates are used in the measurement of  $A_\Gamma$ , while  $y_{CP}$  can be measured with the larger untagged sample.

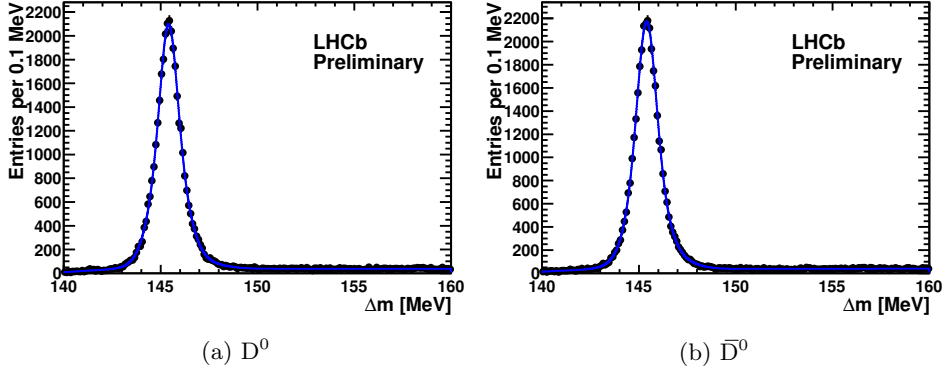


Figure 1: Distributions of the mass difference,  $\Delta m$ , between reconstructed  $D^0$  ( $\bar{D}^0$ ) candidates and their reconstructed parent  $D^{*+}$  ( $D^{*-}$ ) candidates for decays  $D^{*+} \rightarrow D^0\pi^+$ ,  $D^0 \rightarrow K^-\pi^+$  (c.c.).

In the 2010 run, we collected a sample of untagged  $D^0 \rightarrow K^-K^+$  decays comparable in size to those of recent Belle and BaBar measurements.<sup>10,11</sup> In 2011-2012, LHCb expects to have the world's largest charm sample in this mode. The measurements of  $y_{CP}$  and  $A_\Gamma$  are currently blinded. As a test, the  $A_\Gamma$  analysis was applied to a subset of the 2010 data in the right-sign (RS) control channel  $D^0 \rightarrow K^-\pi^+$ . Figure 1 shows the distributions of the differences  $\Delta m$  between the masses of the reconstructed  $D^0$  candidates and their parent  $D^{*+}$  candidates for the RS validation sample. The purity of the sample is better than 90%.

The trigger and selection criteria necessary in LHC collisions introduce a proper-time acceptance for the reconstructed  $D^0$  decays. Levels of combinatoric backgrounds are large near the primary interaction vertex (PV). The most powerful signal/background discriminants exploit the relatively long lifetime of D mesons, requiring some signature of separation between the PV and reconstructed D. Unbiased time-dependent measurements require careful treatment of the acceptance effects of these discriminants. We are pursuing two strategies. The first is to partition the data set into bins of proper time. The observables  $y_{CP}$  and  $A_\Gamma$  can be extracted from the ratios of two proper-time distributions, and hence from the distribution of the ratios of yields in proper-time bins. When the two decay distributions involved have the same final state, as in the case of  $A_\Gamma$ , almost all acceptance effects cancel. The second method is the event-by-event evaluation of the proper-time acceptance by the swimming method.<sup>12,13</sup> For each selected candidate, a single-event acceptance function is calculated by determining whether or not the candidate would have passed the selections had it decayed at a different proper time. This method can be applied exactly to LHCb data with the original trigger and selection software. The acceptance thus evaluated is incorporated into an unbinned fit to the proper time distribution to measure the lifetime.

Another key component of time-dependent charm analysis is the separation of  $D^0$  mesons produced at the PV (prompt) from those produced in the decays of  $b$ -hadrons (secondary).

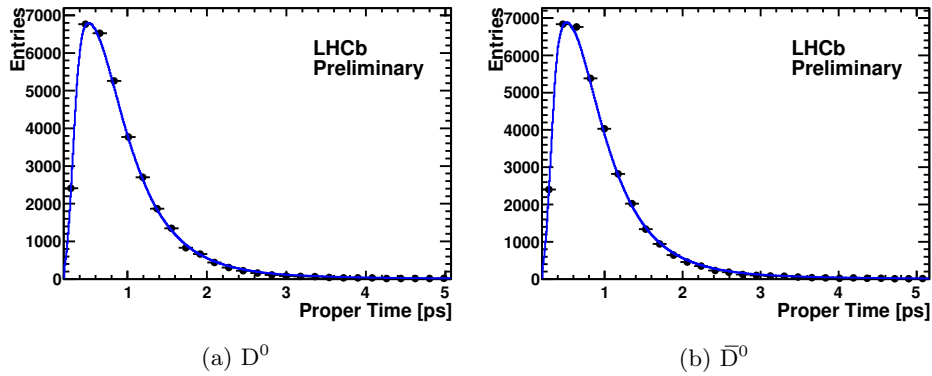


Figure 2: Distributions of the reconstructed proper time of  $D^0$  ( $\bar{D}^0$ ) candidates for decays  $D^{*+} \rightarrow D^0 \pi^+$ ,  $D^0 \rightarrow K^- \pi^+$  (c.c.). The line on each plot is the result of a likelihood fit incorporating per-event acceptance distributions computed with the swimming method.

Because  $b$ -hadrons also fly before decaying, the apparent proper times of secondary  $D^0$  will have a large positive bias. Hence, it is vital to statistically separate the two. The impact parameter (IP)  $\chi^2$  of the  $D^0$  is a powerful discriminant. In the binned lifetime measurement, a fit to the IP  $\chi^2$  is part of the yield measurement in each bin. In the unbinned method with event-by-event acceptance, the IP  $\chi^2$  distribution is incorporated into a multi-dimensional likelihood fit. Figure 2 shows the proper-time distributions for the tagged RS validation sample. The line on the plot is the result of the unbinned multi-dimensional likelihood fit.

#### 4 Summary

LHCb had a successful year of data taking in 2010, collecting  $37.7 \text{ pb}^{-1}$  of pp collisions at  $\sqrt{s} = 7 \text{ TeV}$ . Charm hadron decays were recorded with high efficiency and in large quantities in many channels. We have produced our first precision charm  $CPV$  measurement with this data: the difference between the time-integrated  $CP$  asymmetries of  $D^0 \rightarrow K^- K^+$  and  $D^0 \rightarrow \pi^- \pi^+$  decays is measured to be  $\Delta \mathcal{A}_{CP} = (-0.28 \pm 0.70 \pm 0.25) \%$ . A broad program of charm  $CPV$  and mixing measurements is underway and further results in more channels are soon to follow. The strategies for controlling key systematic effects are mature, and the statistical precision possible with the LHCb data set is already approaching a level comparable with those of the B-factories in key measurements. With the large data set expected in 2011-2012, LHCb is poised to become a leader in charm physics.

1. **LHCb** Collaboration, A. A. Alves *et al.* *JINST* **3** (2008) S08005.
2. **LHCb** Collaboration, Conference Report LHCb-CONF-2010-013, Dec, 2010.
3. S. Bianco, F. L. Fabbri, D. Benson, and I. Bigi *Riv. Nuovo Cim.* **26N7** (2003) 1–200.
4. Y. Grossman, A. L. Kagan, and Y. Nir *Phys. Rev.* **D75** (2007) 036008.
5. **LHCb** Collaboration, Conference Report LHCb-CONF-2011-023, May, 2011.
6. **BaBar** Collaboration, B. Aubert *et al.* *Phys. Rev. Lett.* **100** (2008) 061803.
7. **Belle** Collaboration, M. Staric *et al.* *Phys. Lett.* **B670** (2008) 190–195.
8. **CDF** Collaboration, CDF note 10296, Feb, 2011.
9. **Particle Data Group** Collaboration, K. Nakamura *et al.*, “ $D^0$ - $\bar{D}^0$  Mixing,” in *Review of particle physics*, vol. G37, p. 075021. 2010.
10. **Belle** Collaboration, M. Staric *et al.* *Phys. Rev. Lett.* **98** (2007) 211803.
11. **BaBar** Collaboration, B. Aubert *et al.* *Phys. Rev.* **D80** (2009) 071103.

12. M. Gersabeck, V. V. Gligorov, J. Imong, and J. Rademacker, LHCb Public note LHCb-PUB-2009-022, Nov, 2009.
13. **CDF** Collaboration, T. Aaltonen *et al.* *Phys. Rev.* **D83** (2011) 032008.